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EVIDENCE FOR DIBARYON RESONANCES IN NUCLEON-NUCLEON SCATTERING

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ABSTRACT

There has been a revival of interest in the subject of nucleon-nucleon resonances in the past 3 to 4 years largely generated by experimental results from the polarized beam program at the Argonne ZGS. Evidence from experimental results and phase shift and phenomenological analyses incorporating these results regarding the existence of these resonances is summarized.

INTRODUCTION

From its name one might surmise that a dibaryon is an elementary particle with baryon number B=2. Such particles are exotic states in traditional flavor SU(3), which reproduces the mass spectrum of known hadrons very well. Dibaryons were thought not to exist through the 1960's and most of the 1970's. The prejudice against dibaryons was based on experimental data and the desire for the hadron spectrum to obey the simplest possible symmetry scheme. There was no dynamical reason for six quark objects not to exist: the mechanism of binding and confining quarks to form hadrons is still not well understood. Presently several models predict a spectrum of dibaryons in a bag[1,2] or string[3] picture; in other models there are N-Δ or Δ-Δ states bound by meson exchange.[4] We shall primarily discuss evidence for I=1 dibaryons, since the data for proton-proton scattering is much more copious than that for neutron-proton.

THE I=1 SYSTEM

The major reason for the prejudice against the existence of dibaryons was the absence of any structure in the proton-proton total cross section. Whereas the meson-nucleon total cross sections exibit structure due to the s-channel formation of the low lying N^* resonances, the p-p cross section falls up to about 400 MeV, where the scattering is almost purely elastic, rises smoothly by about 20 mb, and then flattens out around 800 MeV (Fig. 1a).[5] The difference between the elastic (Fig. 1b) and total cross sections above 400 MeV is attributed to the onset of pion production, especially the channel $pp \rightarrow n\Delta^{++}$. It was thus generally believed that there was no structure in nucleon-nucleon scattering other than that due to the NΔ, ΔΔ, NN^*, and N^*N^* thresholds, NΔ being the only one producing noticable energy dependence. There was, however, to the more critical eye structure in several observables centering around 800 MeV (Fig. 2). The total p-p elastic cross section has a broad peak in this vicinity (Fig. 2a).[6] The maximum polarization (-t∿.1-.2) in p-p elastic scattering peaks about 700 MeV[7] (Fig. 2b) and the ratio of the real to imaginary parts of the spin averaged forward scattering amplitude has a zero-crossing at about the same energy[8] (Fig. 2c). Such was the state of affairs in the mid 1970's when systematic measurements of spin observables in p-p scattering were begun in the 1-3 GeV/c energy range.

The measurement[9] of the longitudinal spin-dependent total cross section difference $\Delta\sigma_L$ made by the Argonne polarized target group (Fig. 3) show remarkable structure in the 1-2 GeV/c range, considerably more than the spin-averaged total cross section does. The measurements of the total cross section differences in transverse spin states[10] made by the Michigan and Rice-Houston groups also shows significant structure in this energy range (Fig. 4). The $\Delta\sigma_L$ data has a striking peak at about 1.2 GeV/c (singlet) and an equally striking dip at 1.5 GeV/c (triplet). The $\Delta\sigma_T$ data shows peaks at 1.2 and 2.0 GeV/c (singlet), although due to systematic errors the height of the peak at 1.2 GeV/c is uncertain to within a factor of 1.5-2. (All of these measurements are now being repeated in finer energy steps from 400-800 MeV at LAMPF with hopefully smaller systematic errors. In addition, the lower energy region is being extensively studied at TRIUMPF). The importance of the structure at 2.0 GeV/c is emphasized if $\Delta\sigma_T$ is multiplied by K^2_{in} (Fig. 5), giving an energy independent weight to all the phase shifts. A dispersion analysis[11] indicates a loop in the amplitude ϕ_2 at this momentum which might be interpreted as evidence for a singlet ($^1G_4$) dibaryon resonance. However, this energy is too high for a reliable phase shift analysis; therefore, this structure will not be discussed further.

After the appearance of these data, there was considerable theoretical and phenomenological activity regarding the existence or nonexistence of dibaryon resonances. The phase-shift analysis of Hoshizaki[12] (Fig. 6a) indicated counter clockwise loops in the Argand diagrams for the $^1D_2$ and $^3F_3$ partial waves. (The "nonresonant background" has been subtracted in this analysis). Grein and Kroll[11] have used the imaginary parts of the three spin dependent forward scattering amplitudes gotten from measurements of σ_{TOT}, $\Delta\sigma_L$, $\Delta\sigma_T$, phase shifts at lower energies, and some assumptions about the high energy behavior of $\Delta\sigma_L$ and $\Delta\sigma_T$ to get the real parts of the three forward scattering amplitudes via dispersion relations.

They find a resonant-like structure at 1.5 GeV/c but not at 1.2 GeV/c (Fig. 6b). On the other hand, analyses by Hollas[13], Arndt[14], and Minami[15] argued against the necessity of resonances. Hollas was able to fit the $\Delta\sigma_T$ and $\Delta\sigma_L$ data using arguments from the early work of Mandelstam[16], after separating the total elastic and inelastic cross sections into singlet and triplet parts (Fig. 7). Also the phase shift analysis of Arndt showed no loops in the Argand plots for the $^1D_2$ and $^3F_3$ phase shifts at that time.[14]

Since then the Argonne PPT group has measured C_{LL} at 90° C.M. and 73° C.M. at eleven energies between 1.0 and 3.0 GeV/c[17] (Fig. 8). C_{LL} at 90° shows a dip around 1.2 GeV/c and a peak near 1.5. This would indicate dominance of singlet and triplet partial waves at these respective momenta. Also note that the peak just above 2 GeV/c is absent in the 73° data. Since $P_4(\cos\theta)$ has a zero near this angle, this is perhaps evidence of structure caused by activity in the above mentioned $^1G_4$ partial wave. The Argonne PPT group has gotten the full angular distribution of C_{LL} at these energies, which will shortly be submitted for publication.[18] These data should significantly constrain the phase shift analysis. The recent A and A_{nn} data of the Rice group[7] is shown in Figs. 9 and 10. The energy dependence of A_{nn} (90°) is shown in Fig. 11. There is a striking peak showing triplet dominance at ∿700 MeV, consistent with older data which had large error bars. Fig. 12 shows the D_{NN}, D_{SS}, and D_{LS} data of the LASL-UT-CWRU-TAMU collaboration reported at this conference. These very nice data cover almost the full angular range at 800 MeV, and should place significant constraints on the phase shift analysis. Note that the recent phase shift analysis of Arndt[19] fits all three variables very well, whereas his 1979 analysis[14] gives a much poorer fit. The Argand diagrams for the $^1D_2$ and $^3F_3$ partial waves from this recent energy dependent analysis (Fig. 13) going up to 850 MeV both show loops. This behavior is distinctly different from the 1979 analysis, and in fact a K-matrix calculation reported by Arndt at this conference shows striking $^1D_2$ and $^3F_3$ poles when the scattering amplitude is extrapolated into the complex plane. Finally, there is new data on $\Delta\sigma_T$, pp elastic, and $pp\to d\pi$ from S.I.N. and TRIUMPF presented at this conference which may affect these analyses significantly.

So far we have only discussed the effects on the phase shift analysis of data on total cross sections and elastic scattering. In this energy region various inelastic thresholds are crossed which can give sharp energy-dependent structure to total cross sections and through unitarity possibly to elastic scattering as well.[16,20] Thus the study of the energy dependent behavior of the phase shifts in a coupled channel analysis using all available information on inelasticities seems important. Such an analysis

has been performed by Edwards and Thomas[20] and independently by Arndt as reported at this conference. Some of the results of Edwards and Thomas are shown in Fig. 14a-d for a coupled channel analysis using only elastic and $n\Delta^{++}$ channels. In the first case (14a) the pp→pp is constrained to fit the Arndt phase shifts, the second, Hoshizaki's (14b). The two fits give different values for the $N\Delta \rightarrow N\Delta$ phase shift δ_2.
Nonetheless both fits give a similar loop in the Argand plot for the $^1D_2$ partial wave, and a pole in the K-matrix when extrapolated to the complex plane (14c-d). The analysis has been extended to include the $d\pi^+$ channel and extended up in energy to investigate the $^3F_3$ around 800 MeV. In this 3-channel analysis K-matrix poles were found in the $^1D_2$ and $^3F_3$ amplitudes.[21] Similar results were reported here by Arndt.
Kloet and Silbar[22] have calculated the p-p elastic phase shifts in a unitary dynamical model using π, ρ, σ, σ', and ω exchanges, for different values of the various coupling constants. In particular, the short range forces (ρ and ω exchange) were varied in strength over a wide range. For "reasonable" values of the coupling constants the $^1D_2$ and $^3F_3$ amplitudes show counterclockwise rotation in the Argand diagrams similar to Arndt's recent phase shift analysis (Fig. 15). This result is not surprising since this dynamical model was constructed to reproduce Arndt's phase shifts.

Umland and Duck have calculated cross sections and single spin asymmetries for $pp \rightarrow pn\pi^+$ at 800 MeV (reported by Umland). Results for a single production and decay angle of the Δ are shown in Fig. 16a-b. The fit to the cross section (this data reported here by Hancock) is improved by adding s-channel $^3F_3$ and $^1D_2$ dibaryon amplitudes to the π and ρ exchanges. However, the fit to the asymmetry data is improved much more dramatically by this addition. On the other hand, even when the couplings are adjusted to fit the cross sections roughly, meson exchange alone gives asymmetries which do not resemble the data at all.

None of these analyses or the data used as input conclusively prove that I=1 dibaryons resonances exist; indeed, some of the analyses were begun with the opposite intent. However, there is increasing experimental evidence for structure in nucleon-nucleon cross sections and spin observables, and increasing evidence from theoretical analyses for counter clockwise rotation of Argand plots and for poles in the complex plane in various partial waves.

THE I=0 SYSTEM

Because of time constraints we shall comment only briefly on the I=0 system, where the data is, in general, much sparser due to the greater difficulty of making neutron-proton measurements and subsequently subtracting the I=1 parts. Neutron-proton total cross section measurements[23] are shown in Fig. 17. We remember that the n-p system does not have a strong N-Δ threshold, and therefore, the total cross section does not reach a maximum until above P_{lab} = 2 GeV/c, distinctly different from p-p (Fig. 1). Although the n-p cross section rises much slower than p-p, there is a shoulder around 1.5 GeV/c, which is made more visible by the absence of the strong N-Δ threshold present in p-p. Measurements of the Argonne group of $\Delta\sigma_L(I=0)$[24] are shown in Fig. 18. These data are obtained by measuring $\Delta\sigma_L(pd)$, then subtracting $\Delta\sigma_L(I=1)$ after attempting to take into account affects due to screening, rescattering, and Fermi motion inside the deuteron, very difficult procedures. Nonetheless, there is a clear peak at 1.5 GeV/c, which has been interpreted as evidence for a $^1F_3$ dibaryon resonance,[25] which may plausibly exist if the $^3F_3$ does. Data on $\Delta\sigma_T(pd)$ taken by the Rice group immediately before the ZGS shutdown, which is presently under analysis, should help to resolve this question, since the same singlet enhancements should appear in $\Delta\sigma_T$ and $\Delta\sigma_L$. However, the analysis is subject to the above mentioned difficulties in addition to a considerable uncertainty in the knowledge of the deuteron polarization in the target. Japanese groups[4] also have found an anomalous peak in the proton polarization in the photodisintegration of the deuteron at $\sqrt{s}\sim$2400 MeV. They are able to fit the data by adding a Breit-Wigner-type amplitude for a Δ-Δ bound state with this mass (Fig. 19a), whereas without any resonances they are unable to account for the large polarization (Fig. 19b). Thus there is some evidence for structure in the n-p system not associated with inelastic thresholds, but data is sufficiently sparse in this energy range that we are far from having a reliable phase shift analysis.

EPILOG

Finally let us briefly discuss one additional topic. There has been some recent speculation and evidence from lower energy accelerators, in particular, TRIUMPF and LAMPF, that some of the lowest energy data from Argonne may be in error. In particular, at 1.2 GeV/c, the earliest $\Delta\sigma_T$ point has been found to be low by subsequent yet to be published measurements at Argonne and LAMPF, and similarly the $\Delta\sigma_L$ point may be somewhat in error, both possibly due to unknown depolarization of the beam in the ZGS and the difficulties of handling the low momentum beams at the ZGS. For this reason, the experiments now in progress at TRIUMF, S.I.N., and LAMPF are particularly important; hopefully high quality data will be obtained which will help settle the question of the existence of dibaryon resonances. My personal belief is that despite quantitative errors in the early data, the qualitative results are correct, i.e., there are structures at 1.1-1.2 GeV/c and at 1.4-1.5 GeV/c associated with singlet and triplet enhancements, respectively.

I very much appreciate the hospitality shown by the organizers of this conference, particularly Dr. B. Bonner and Dr. G. Ohlsen. I am particularly grateful to Dr. A. Yokosawa for making available data and other information relevant to this subject. I am also grateful to Dr. G. Thomas, Dr. M. Johnson, Professor E. Lomon, and Professor I. Duck for illuminating discussions.

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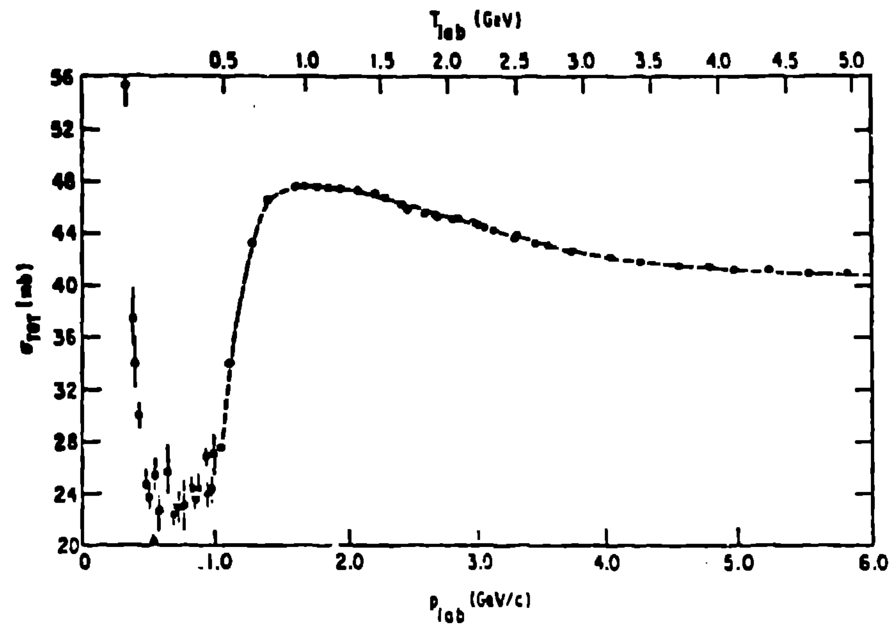


Fig. 1a. Proton-proton total cross section.

Fig. 1b. Total elastic p-p cross section.

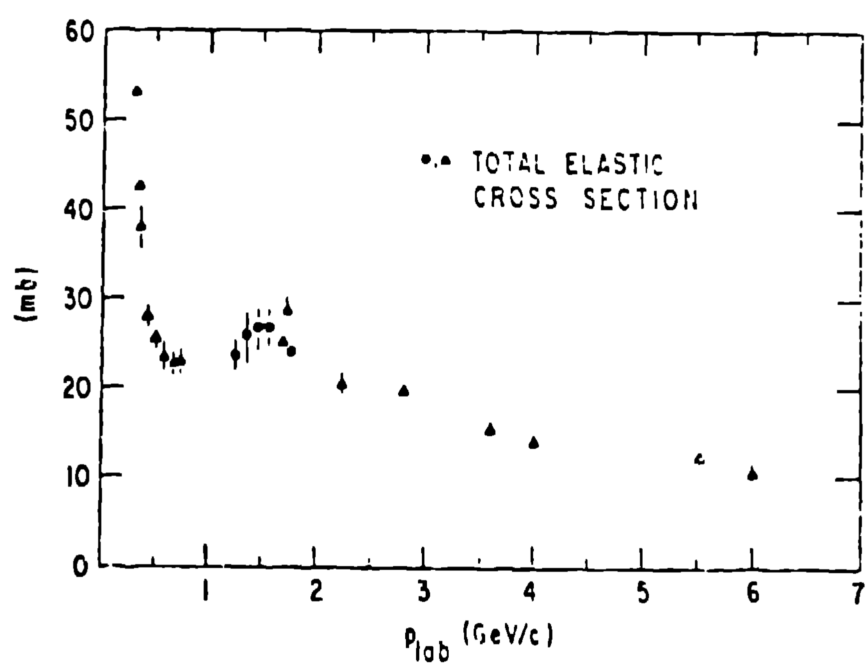


Fig. 2a.

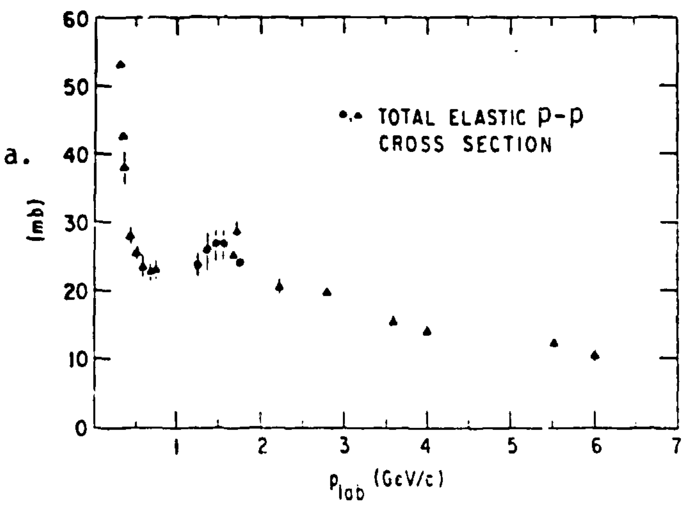
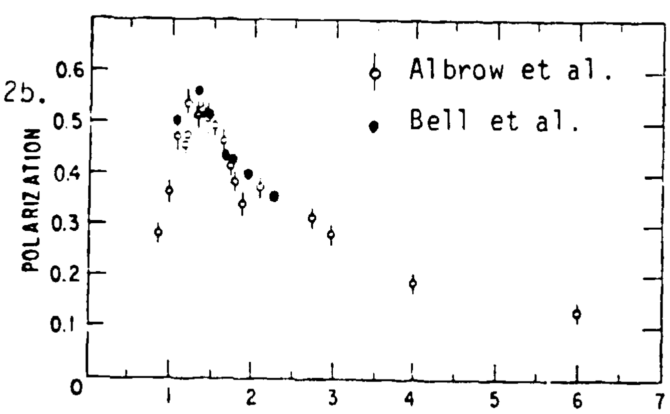


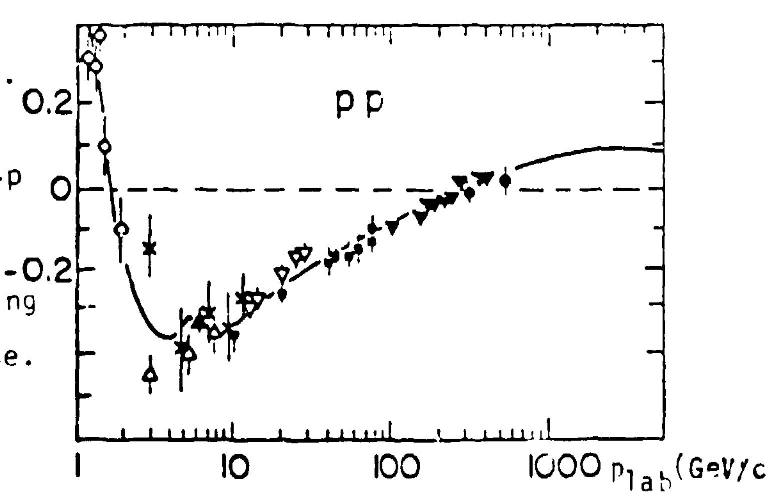
Fig. 2b.



Maximum polarization in p-p elastic scattering.

Fig. 2c.

Re/Im p-p forward scattering amplitude.



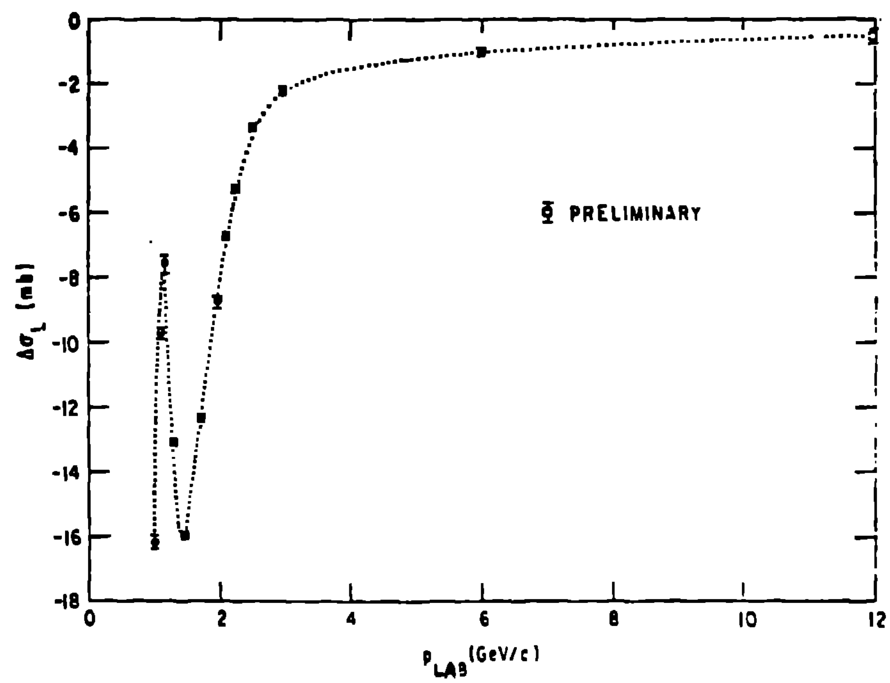
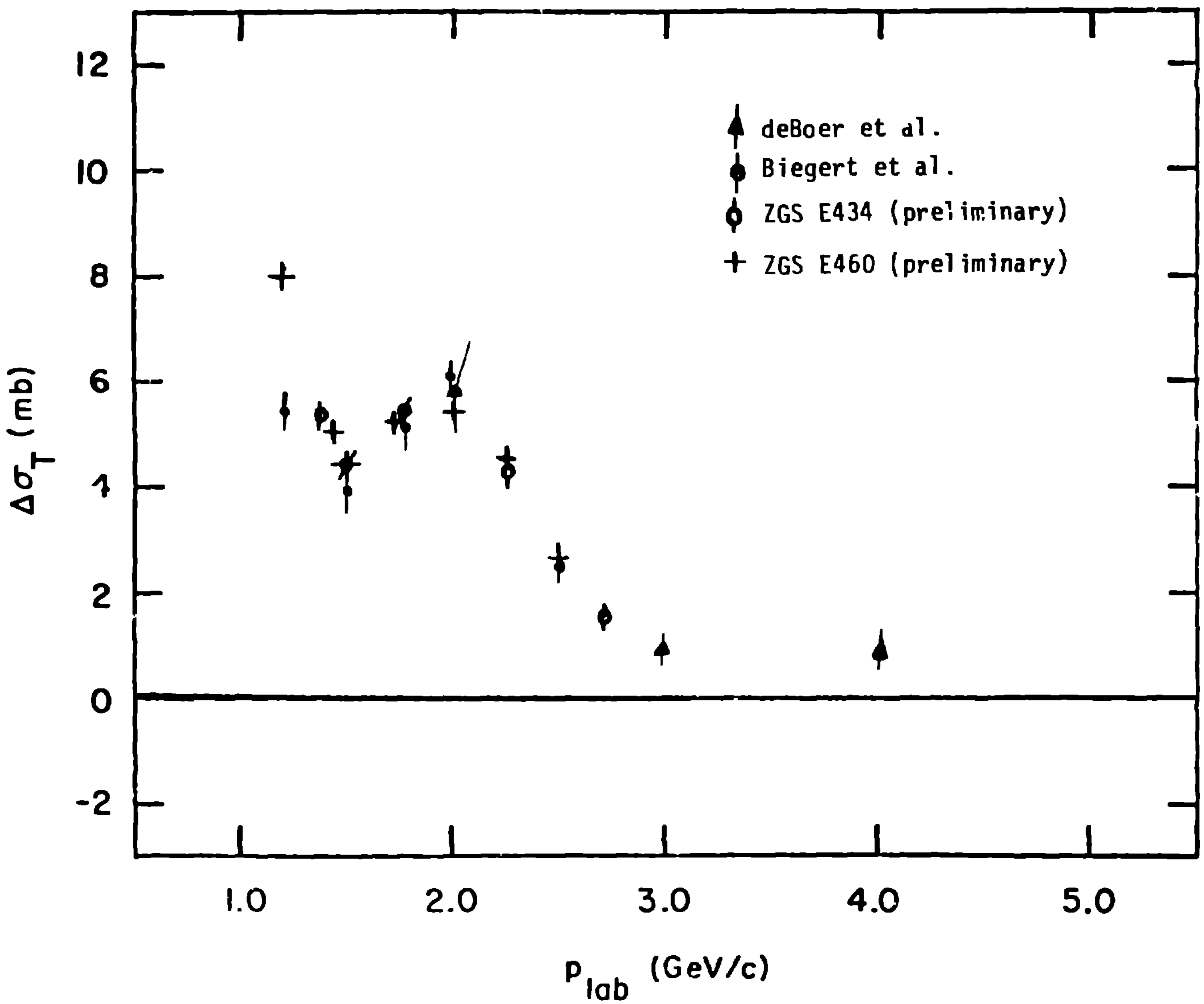


Fig. 3. Total cross section difference, $\Delta\sigma_L$, 1-12 GeV/c.

Fig. 4. Total cross section difference, $\Delta\sigma_T$, 1-3 GeV/c.



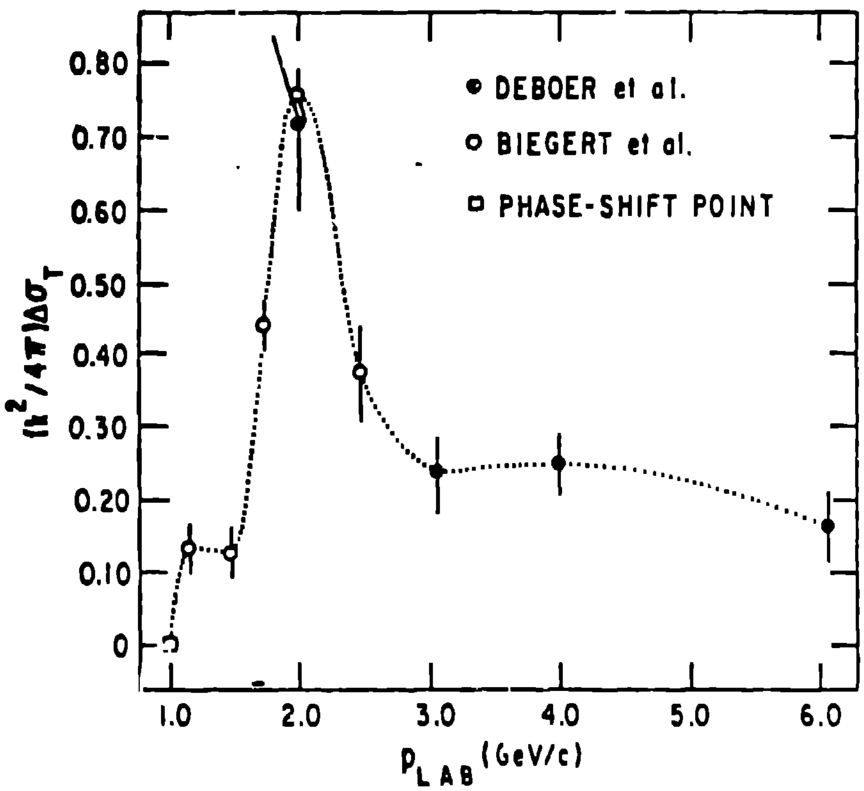


Fig. 5. $K^2_{cm}/4\pi \ \ \Delta\sigma_T$.

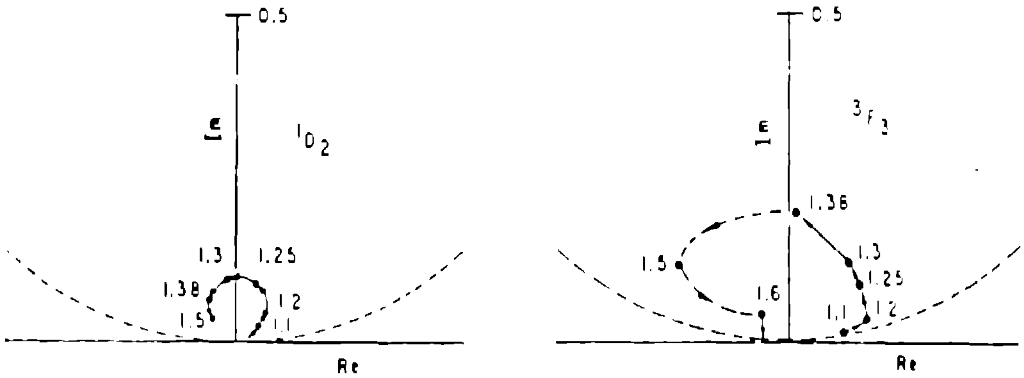


Fig. 6. $^1D_2$ and $^3F_3$ phase shifts from analysis of Hoshizaki.

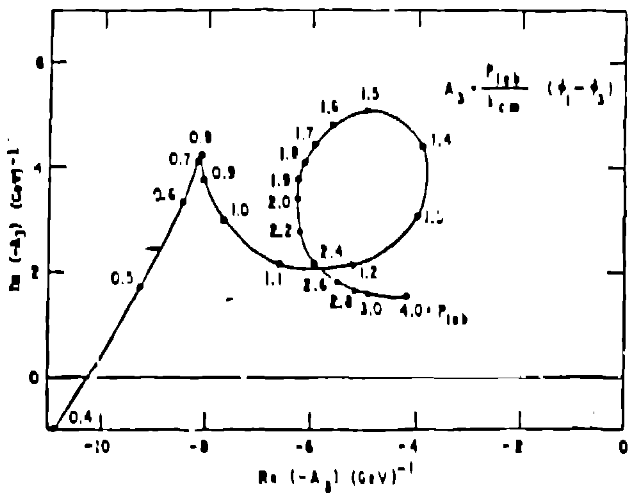


Fig. 7. Argand diagram from analysis of Grein and Kroll.

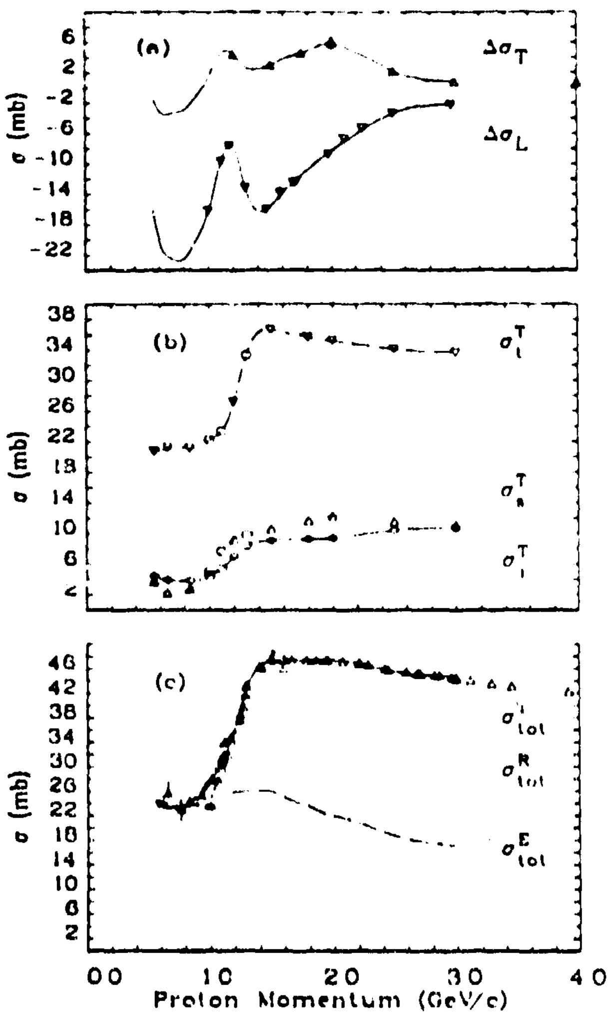
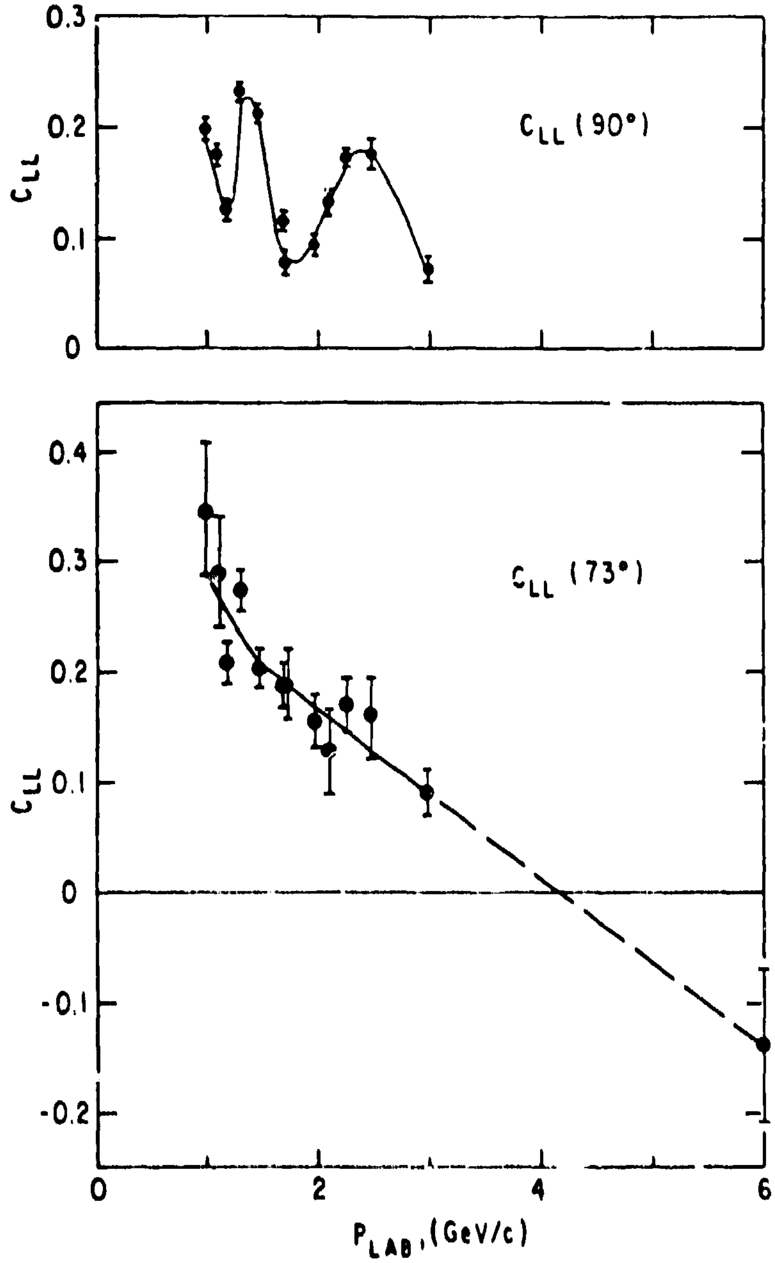


Fig. 8. The momentum dependence of (a) the cross section differences $\Delta\sigma_T$ and $\Delta\sigma_L$ (the data are from Refs. 1 and 2; the curves are described in the text); (b) the singlet (σ_s^T), triplet (σ_t^T), and triplet-interference (σ_i^T) cross sections, as described in the text. (c) the spin-averaged total cross sections, σ_{tot}^T (triangles), σ_{tot}^R (dotted line), and σ_{tot}^E (dashed line).

Fig. 9. C_{LL} for p-p elastic at two C.M. angles.



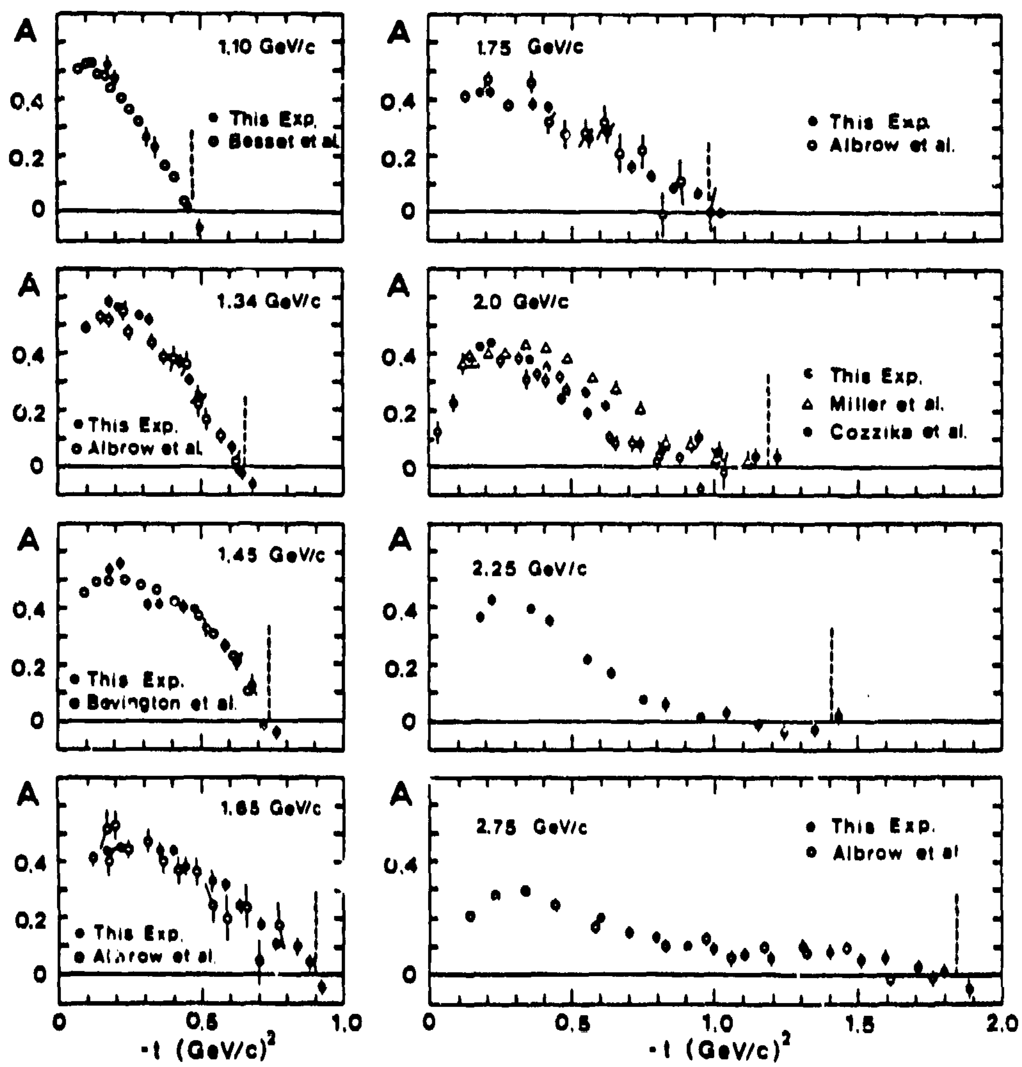


Fig. 10. p-p polarization, 1.1-2.75 GeV/c.

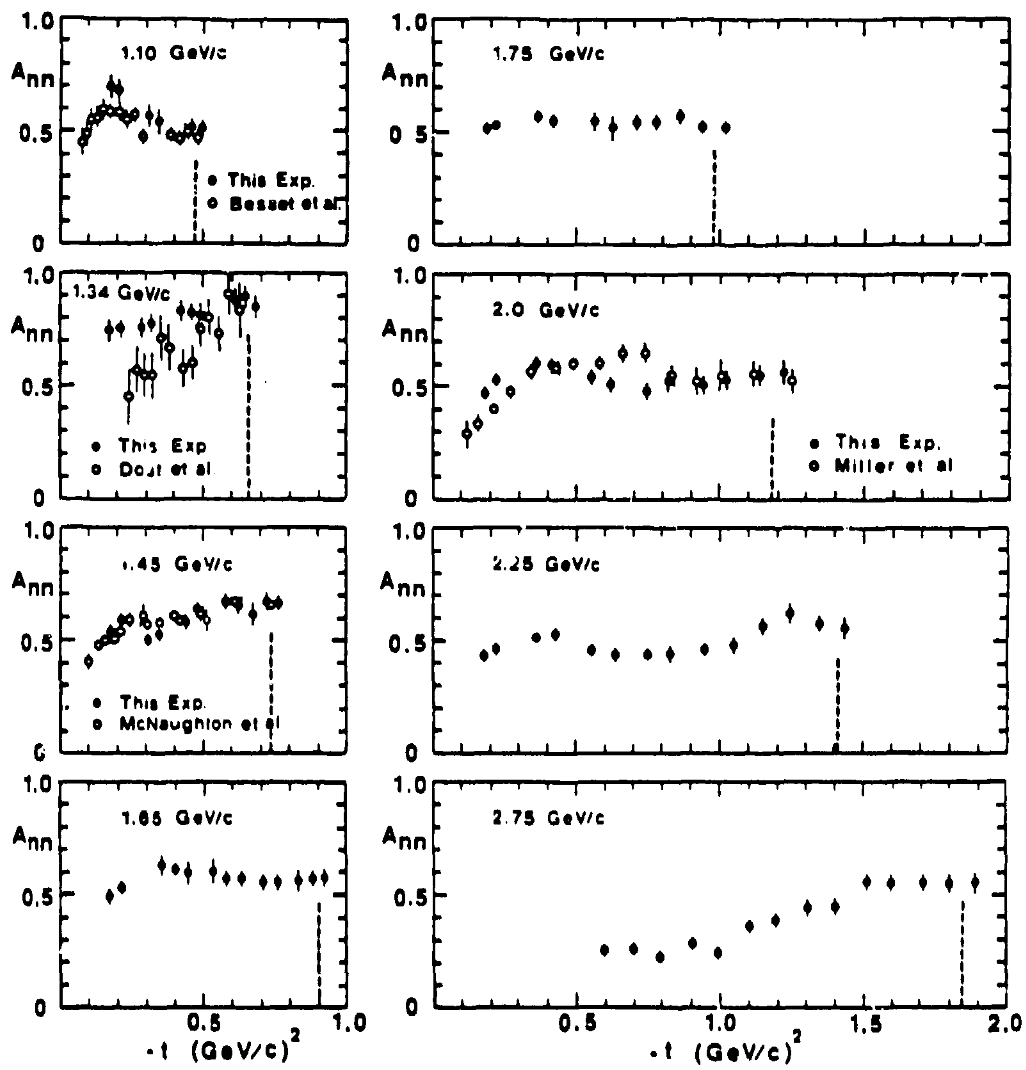


Fig. 11. A_{nn} for p-p elastic, 1.1-2.75 GeV/c.

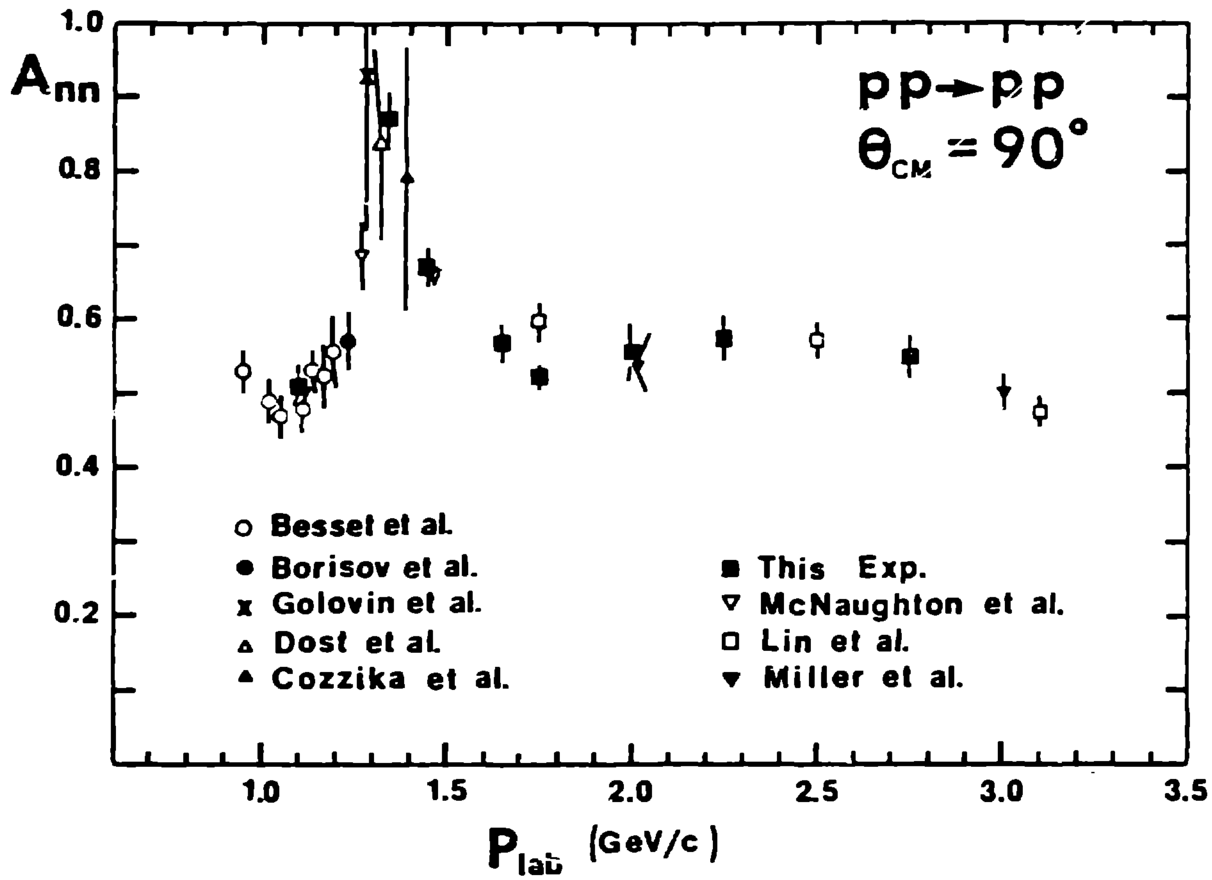


Fig. 12. A_{nn} for p-p elastic at 90° C.M.

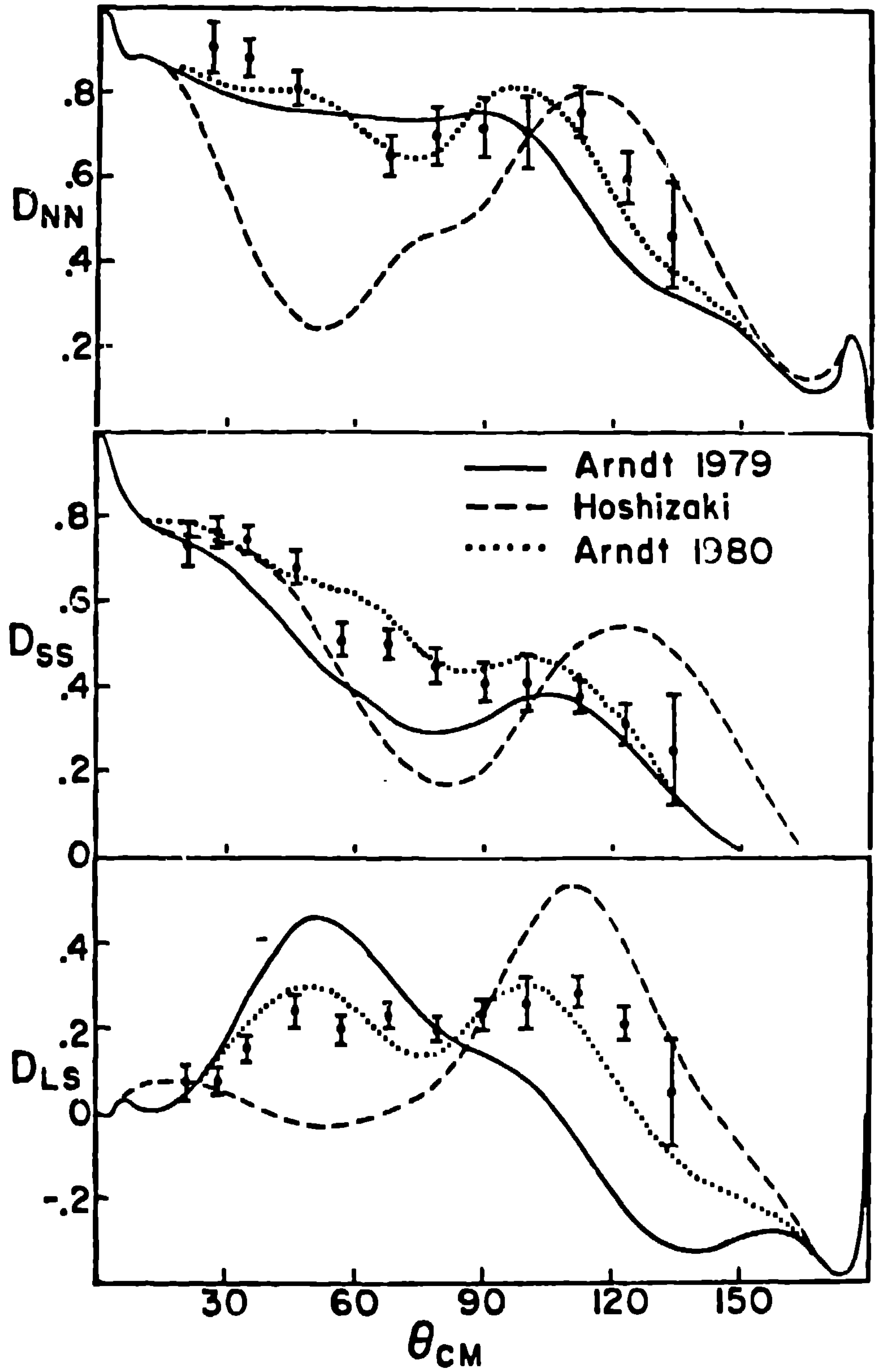


Fig. 13 D_{NN}, D_{SS}, and D_{LS} for p-p elastic scattering at 800 MeV.

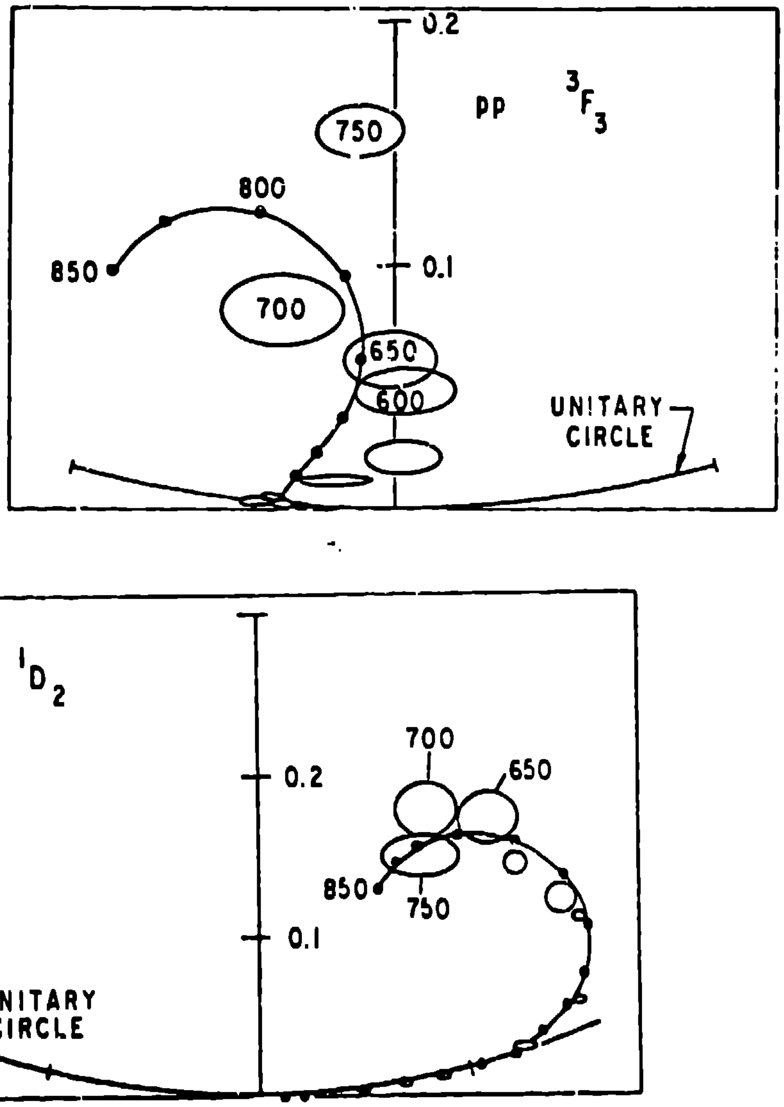


Fig. 14.
Argand diagrams of the $^3F_3$ and $^1D_2$ partial waves based on Arndt's phase shifts. The ellipses represent the errors in the real and imaginary parts of the amplitudes for energy-independent solutions. The continuous curves represent the energy-dependent solutions.

Fig. 15a. Phase shift δ_2 for $N\Delta \to N\Delta$ calculated in coupled channel analysis using δ_1 and η from Arndt's phase shifts (Ref. 20).

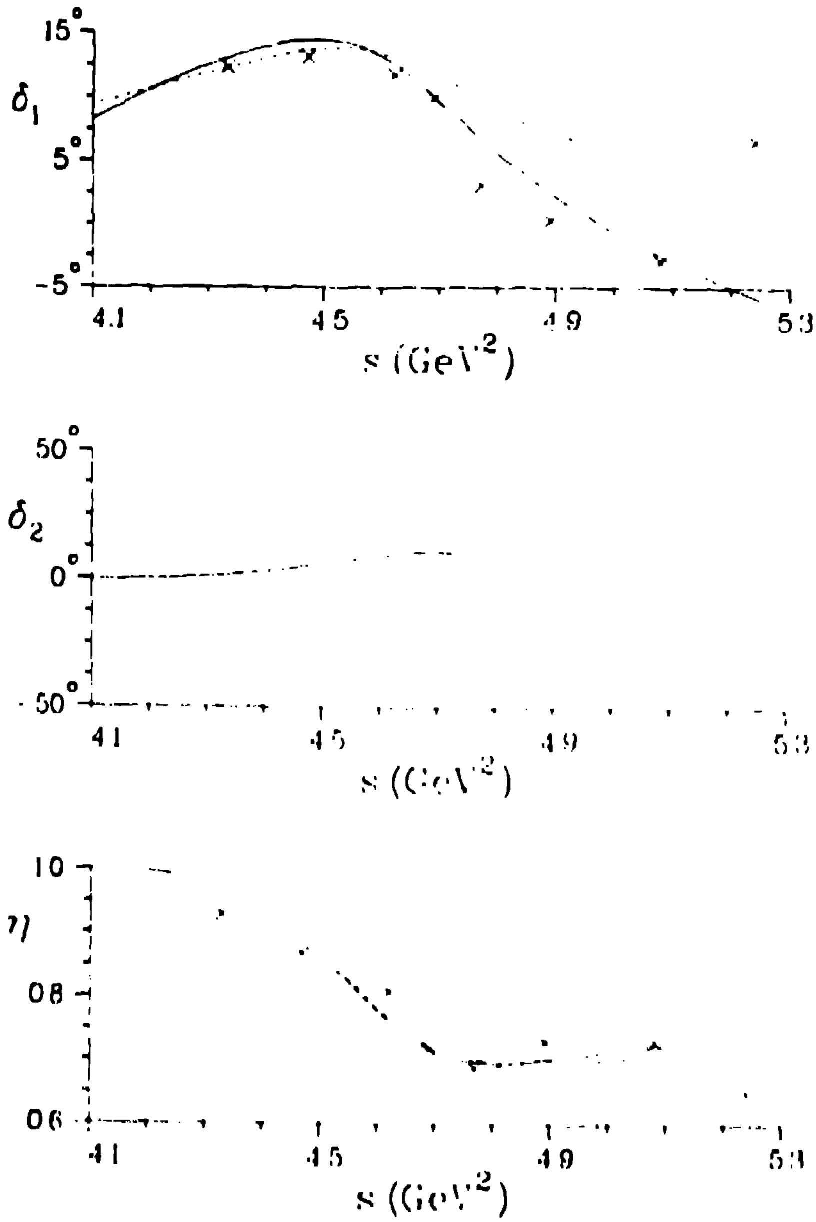
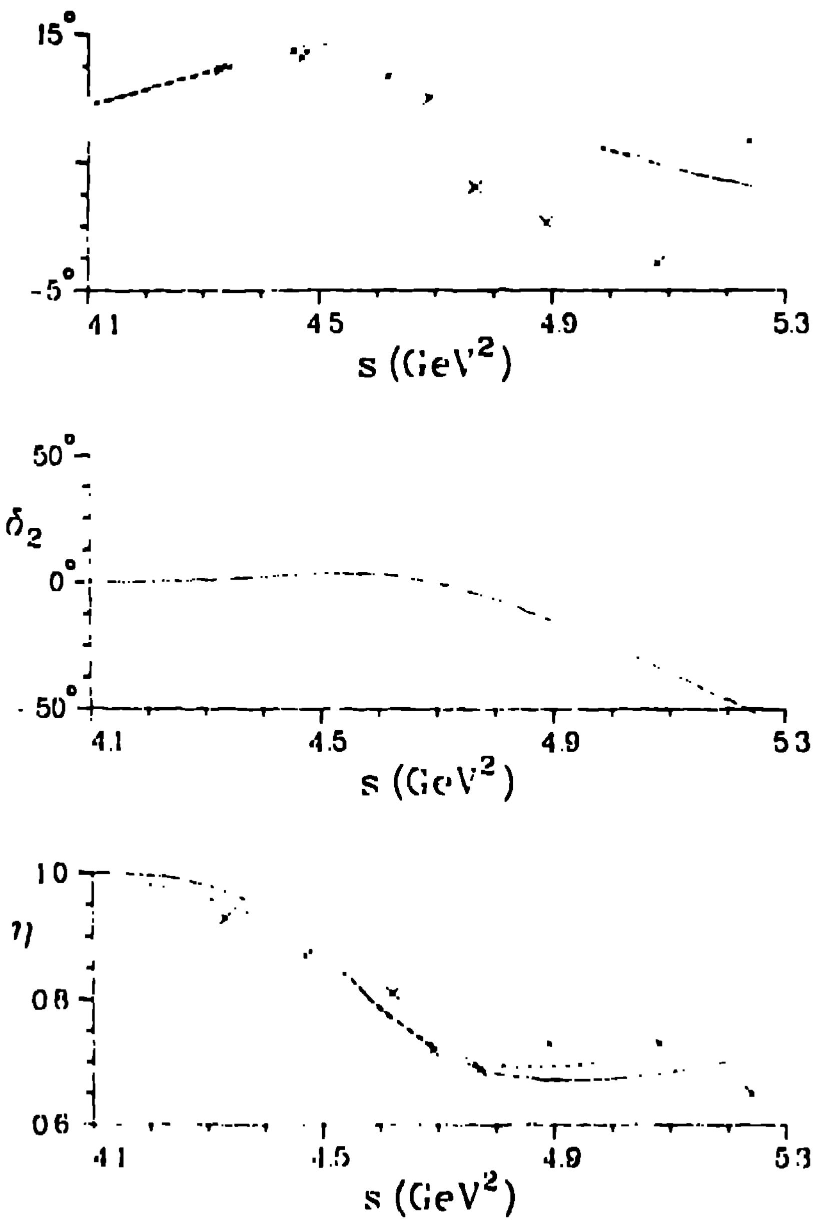


Fig. 15b. Same as 15a, using Hoshizaki's phase shifts.



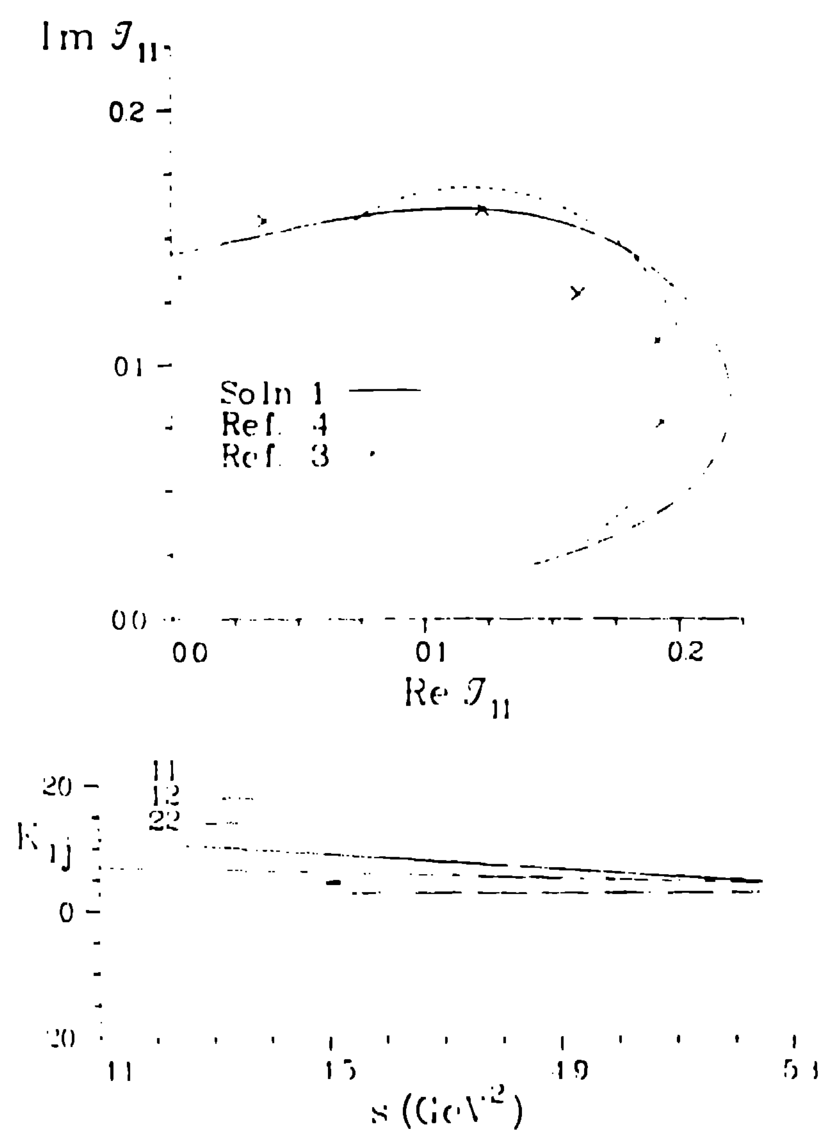


Fig. 15c. Argand plot for $^1D_2$ and K-matrix from calculation of Ref. 20 using phase shifts from 15a.

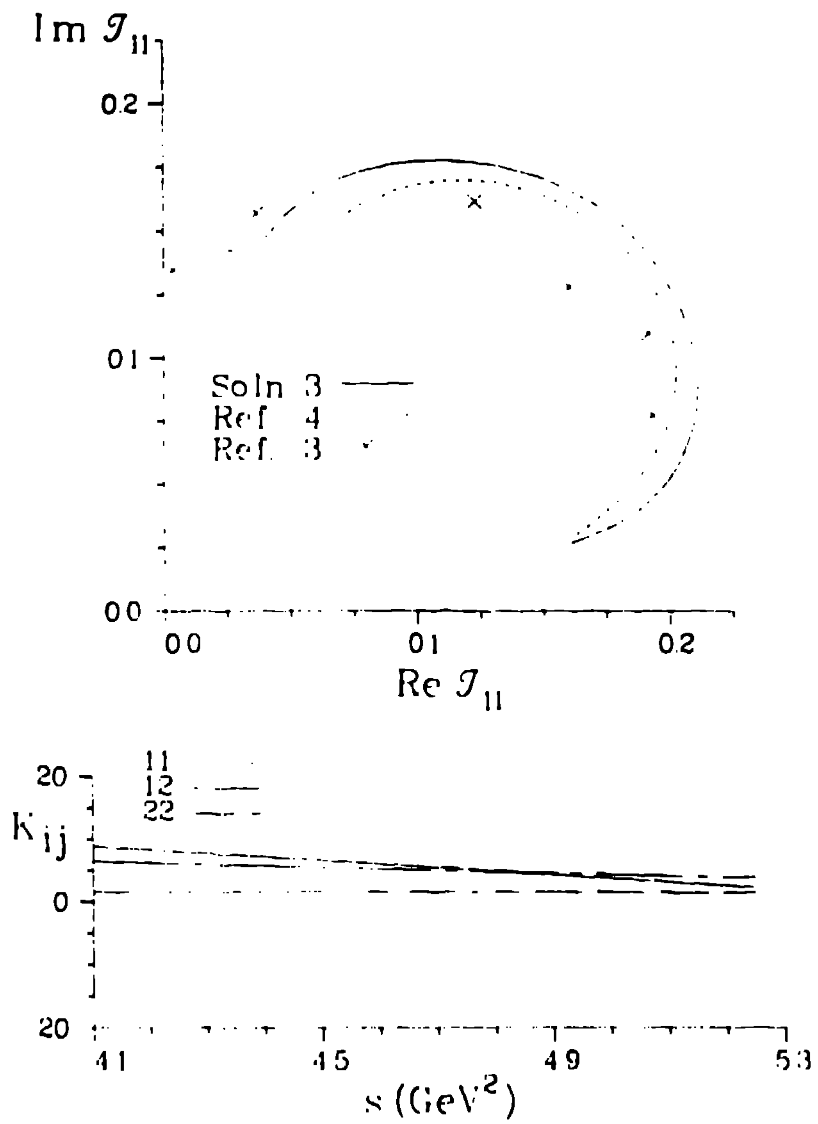


Fig. 15d. Same as 15c, using phase shifts from 15b.

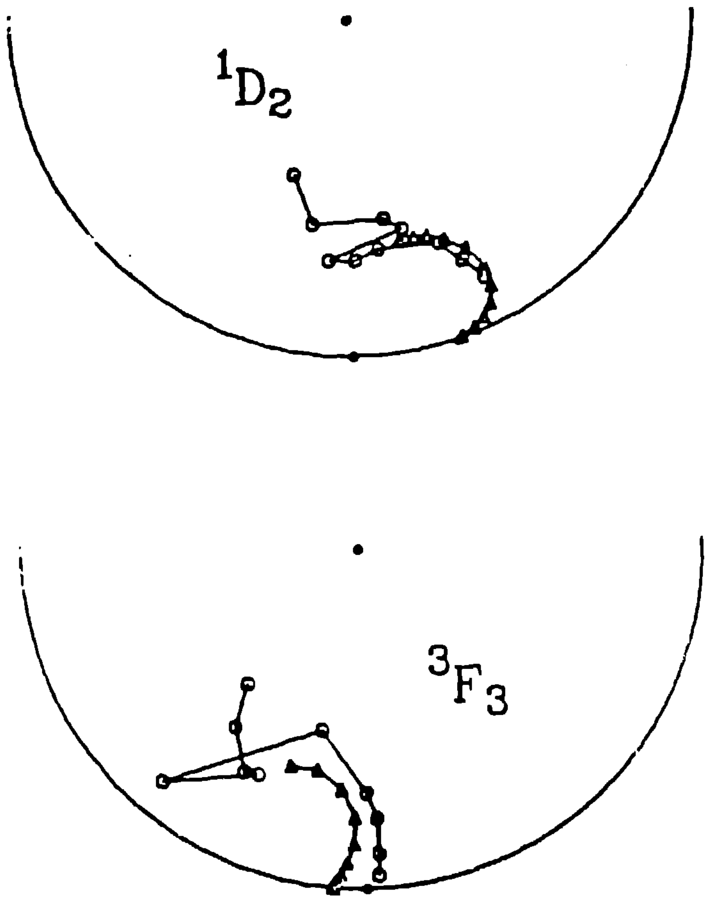


Fig. 16. Sample Argand diagram for $^1D_2$ and $^3F_3$ from unitary dynamical model of Kloet and Silbar.

Fig. 17a. Calculation of cross section $d^5\sigma/dp d\Omega_1 d\Omega_2$ for $pp \to pn\pi^+$ of Umland and Duck using only meson exchange and adding $^1D_2$ and $^3F_3$ dibaryon amplitudes.

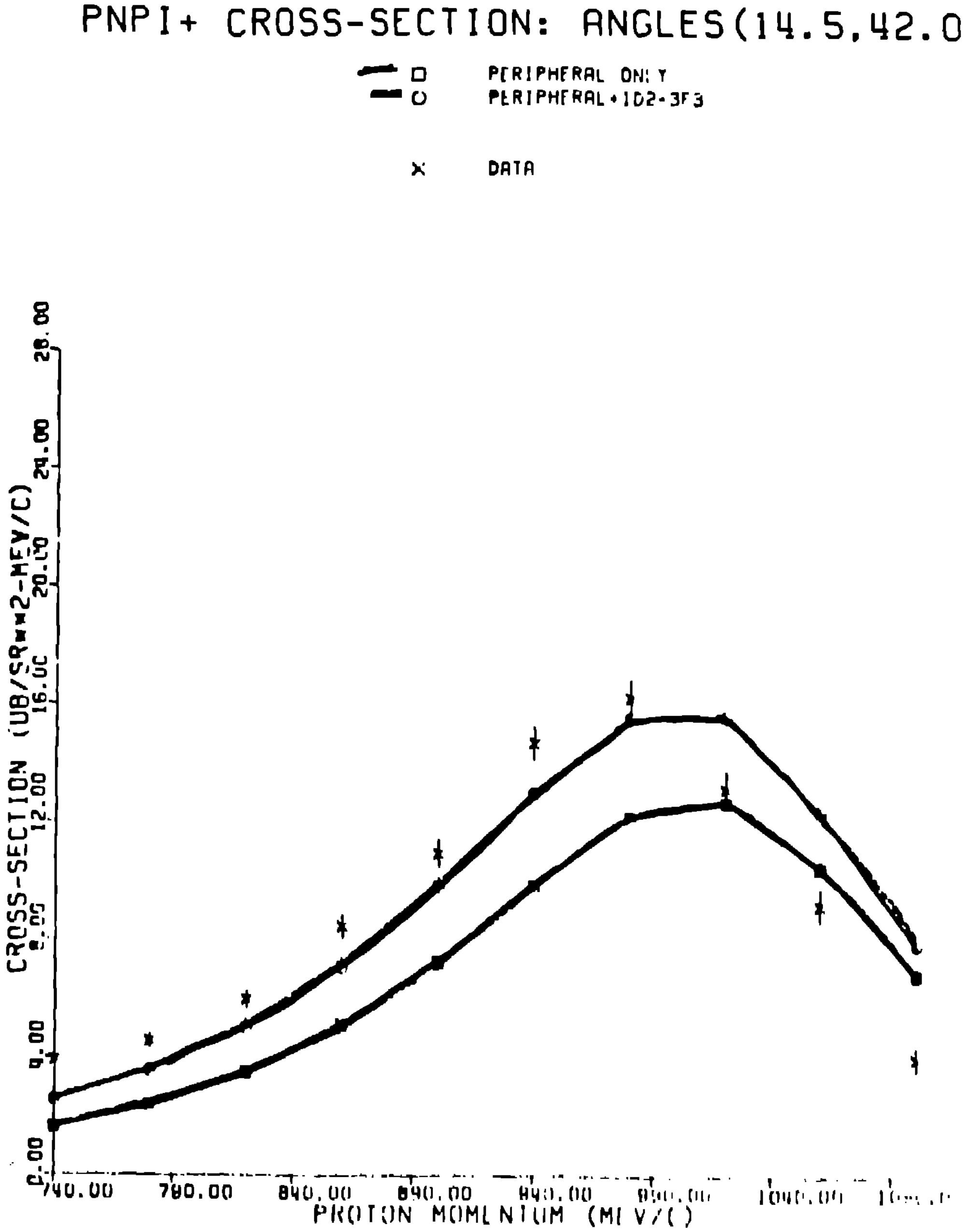
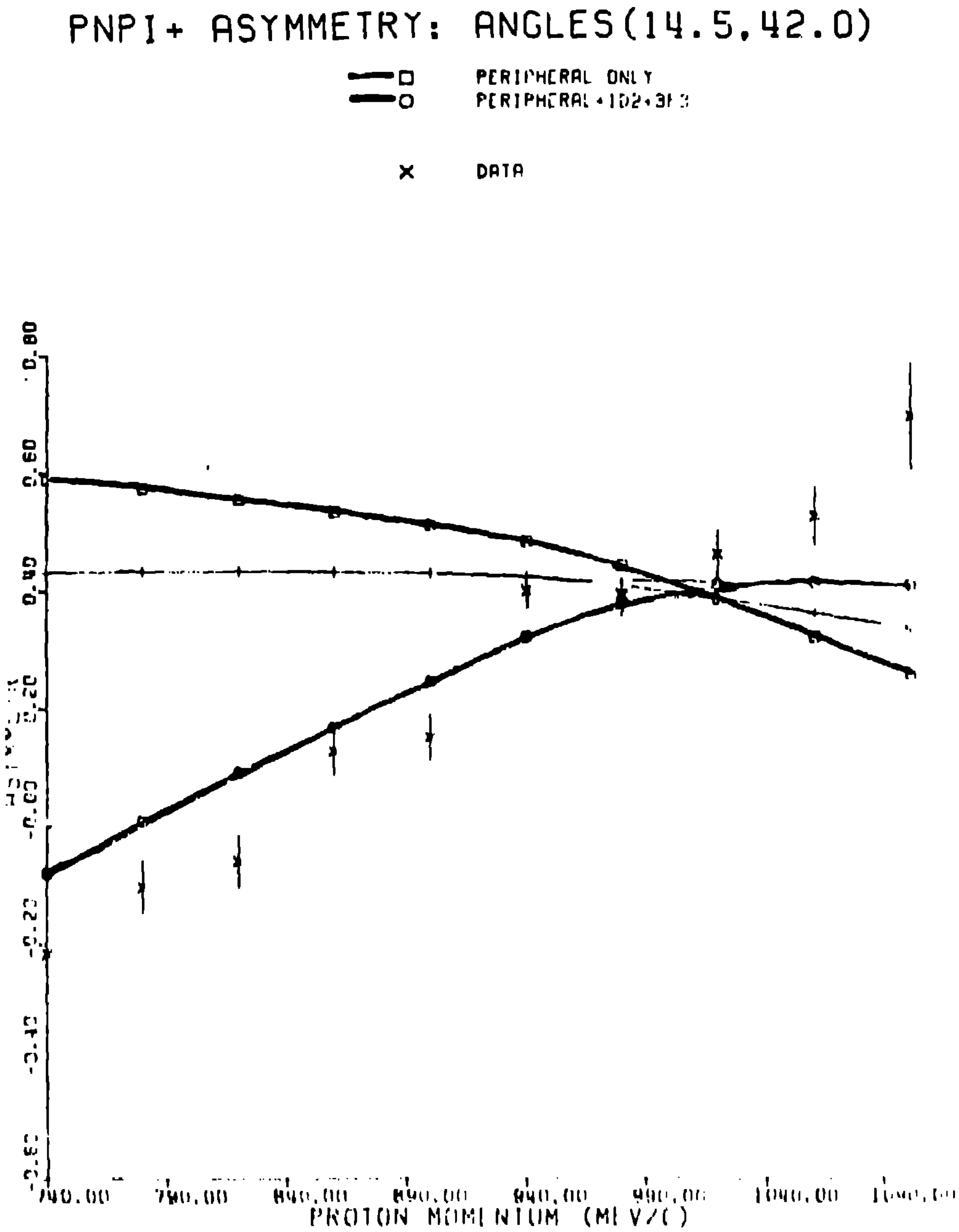


Fig. 17b. Similar calculation to 17a of single spin asymmetry in pp→pnπ⁺.



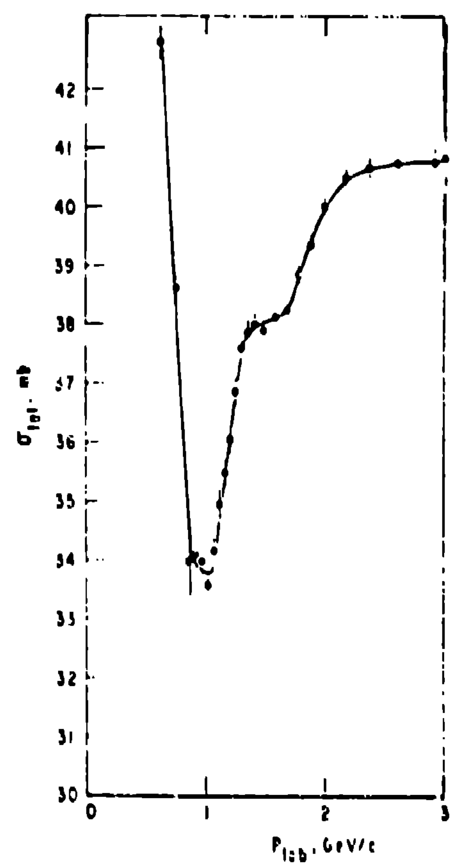


Fig. 18. Neutron-proton total cross section (Ref. 23).

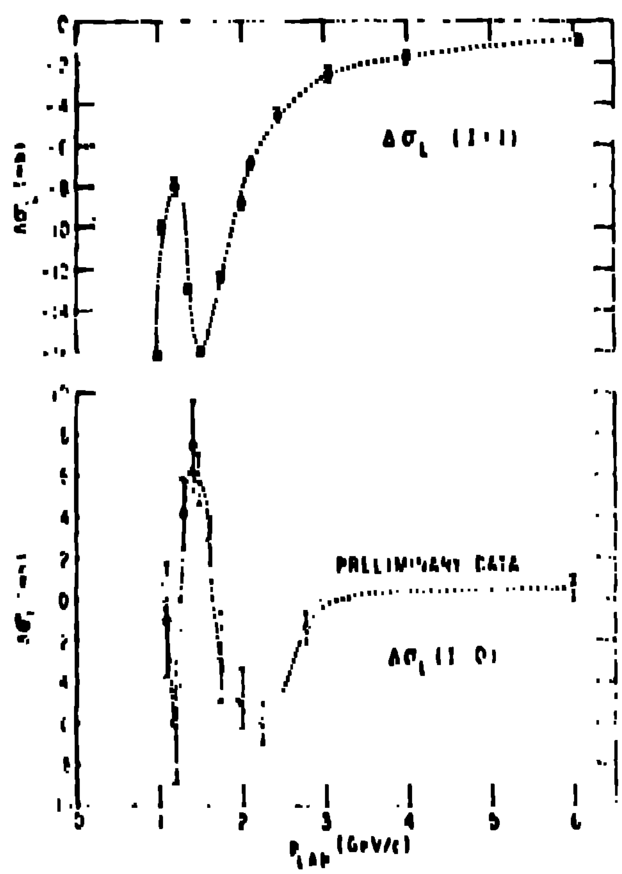
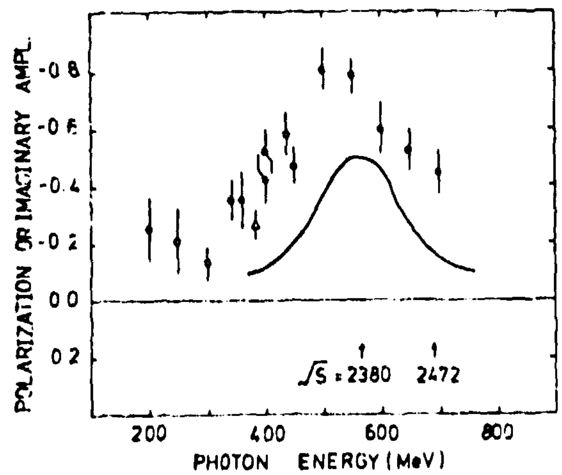


Fig. 19. $\Delta\sigma_L(I=0)$ extracted from $\Delta\sigma_L(pd)$ and $\Delta\sigma_L(I=1)$ plotted along with $\Delta\sigma_L(I=1)$.

Fig. 20a.

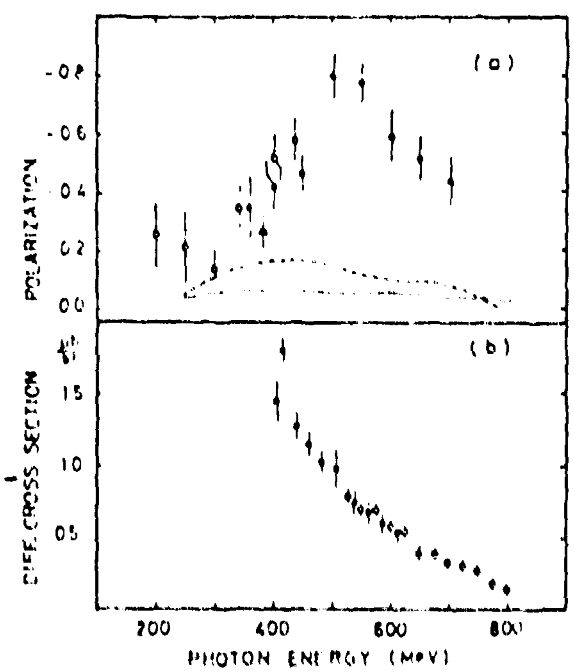
(Ref. 4).



Proton polarization in $\gamma d \to pn$. Filled circles are data from Ref. 1, open circles are data from Ref. 5 of Ref. 1, and triangle is datum from Ref. 6 of Ref. 1. The curve shows the Breit-Wigner-type imaginary and amplitude due to the ΔΔ bound state at $\sqrt{s}$ = 2380. Note that the unbound ΔΔ phase space opens at $\sqrt{s}$ = 2472.

Fig. 20b.

(Ref. 4).



(a) Proton polarization at 90° c.m. system as a function of the photon energy. The solid and the dashed curves are the results of a relativistic-covariant computation and a phenomenological analysis respectively (see Ref. 10). Data points are from Ref. 5 (open circles), Ref. 6 (triangle), and the present experimental (filled circles). (b) Differential cross section at 90° c.m. system as a function of the photon energy. Data points are taken from Ref. 1 (open circles) and Ref. 2 (closed circles).